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A combination equation for potential transpiration (E_t) and the evaporation from wet surfaces (E_p)

B G Wales-Smith

1. Requirements: The transpiration equation must

   (a) have physical realism,

   (b) be supported by theory and established results and hence be generally acceptable,

   (c) be readily solvable using basic meteorological data,

   (d) be suitable for making long-period (eg monthly) estimates of E_t from simple averages of screen temperature and vapour pressure, wind speed and duration of bright sunshine, with reasonable assumptions about catchment roughness, soil heat flux and the bulk aerodynamic and stomatal resistances,

   (e) be suitable for making accurate estimates of E_t using an hourly time-step and with measured or calculated values of roughness, heat flux and resistances,

   (f) have obvious comparability with Penman's original equation (Penman, 1948) for potential evaporation so that established results (obtained with Penman's E_{tp}) can be re-assessed without difficulty,

   (g) be capable of being solved economically by computer for MORECS (Meteorological Office Rainfall and Evaporation Calculation System) (Wales-Smith, Prior and Arnott, 1977 , Wales-Smith and Arnott, 1979.)

   (h) be readily adaptable to give an estimate of the evaporation rate from wet vegetation.

2. A combination equation for potential transpiration has been dervied from that due to Penman (1948) as follows:

$$E_t = \frac{\Delta}{\Delta+(1+r_{sdn}/r_a)\gamma}\left\{(1-r)R_c+G-\cdot 95R_{LN}\right\} + \frac{m\gamma}{\Delta+(1+r_{sdn}/r_a)\gamma}\left\{0{\cdot}26\left(1+\frac{u_2}{100}\right)(e_a-e_d)\right\}$$ following Thom and Oliver (1977). *

where R_c = total solar radiation, is obtained from

$$R_c = R_a\left\{d(a+b\,n/N)+(1-d)c\right\}$$ (equiv. mm. of water evaporated).

, the revision of the Angstrom (0.925) equation being due to Cowley (1978),

where r = albedo (short-wave), r_L = albedo (long-wave)

R_a = total possible radiation for latitude and time of year

d = 1 for days with bright sunshine

= 0 for days without bright sunshine

a, c } vary with location

b = varies with location and season

n = measured duration of bright sunshine

N = total possible duration of bright sunshine for lat. and time of year.

* with the addition of the factor 0.95 (= 1−r_L)

G = measured soil heat flux, expressed in equiv. mm of water evaporated.

≈ a function of change of soil temperature with time

≈ 10% of R_N (into soil by day - out of soil by night) R_N = net radiation,

≈ average monthly values which can be sub-divided to shorter periods,

(Wales-Smith and Bader, 1978)

R_{LN} = net long-wave radiation for a black body surface.

$= \sigma \overline{T_a}^4 B(0.56 - 0.08\sqrt{e_d})(0.10 + 0.90\, n/N)$ (equiv. of water evaporated)

where $\sigma \overline{T_a}^4$ = black body radiation at screen temperature $\overline{T_a}^{\circ}K$. 0.95 is used because green vegetation does not radiate as a perfect black body. (Grindley, 1970; Budyko, 1956) and is thus an allowance for long-wave albedo.

B is a seasonal, empirical factor (Wales-Smith 1978)

e_d = screen vapour pressure (mb)

$= \left[\sigma\left\{1.03\,\overline{T_a}^4 - T_s^4\right\} - 113\right](0.10 + 0.90\, n/N)$. (Thompson, 1978)

where

T_s = surface temperature (this can be estimated via a series of calculations)

$m = \left[\dfrac{\ln(z/z_{cp})}{\ln(z/z_o)}\right]^2$ a catchment aerodynamic roughness parameter depending on vegetation and season, to be approximated, held in a data-set or obtained by more rigorous methods.

r_{sdk} = bulk stomatal resistance (for freely transpiring dry vegetation) - values depending on vegetation and season to be held in a data-set

r_a = bulk aeradynamic resistance

$= \dfrac{\{\ln(z/z_o)\}^2}{k^2 \beta u}$

z/z_c to be held in a data-set, by vegetation and season

$k \approx 0.4$ (von Karman's constant)

u = wind speed (ms^{-1})

β = a factor to relate "crop" roughness to grid-square (MORECS) roughness

In the above it has been assumed, for any location, that given "crops" reach given stages of development by given dates. A running balance of cumulative departure of average screen temperature from long-term means could be used to model departures of growth from average, this would be reflected in r_a and m and in albedo values.

u_2 = run of wind at 2m above ground ($Km.day^{-1}$)

e_a = saturation vapour pressure at screen temperature (mb)

The term $0.26\left(1 + \frac{u_2}{100}\right)(e_a - e_d) = E_{a-p}$, is in equiv. mm of water evaporated.

3. The following simple scheme describes the method of calculating evaporation by day and night and transpiration by day

Day

Surfaces dry

Soil moist

Stomata open

Transpiration = E_t

Night

Surfaces dry

Stomata closed

No transpiration

Calculate E_p

E_p < 0 net excess of condensation over evaporation

E_p ≥ 0 disregard

Surface wet

No transpiration until intercepted water evaporated

Evaporation = E_p

$$E_p = E_t \left\{ \frac{\Delta + (1 + r_{sdn}/r_a)\gamma}{\Delta + \gamma} \right\}$$

E_t = potential transpiration

E_p = potential evaporation from a wet surface

-ve E_p = net excess of condensation over evaporation

E_t is a "stage" in calculating E_p

$$E_t = \frac{\Delta}{\Delta + (1 + r_{sdn}/r_a)\gamma} \{R_N + G\} + \frac{m\gamma}{\Delta + (1 + r_{sdn}/r_a)\gamma} E_{ap}$$

Surface wet

No transpiration

Evaporation = E_p

$$E_p = E_t \left\{ \frac{\Delta + (1 + r_{sdn}/r_a)\gamma}{\Delta + \gamma} \right\}$$

$$E_t = \frac{\Delta}{\Delta + (1 + r_{sdn}/r_a)\gamma} \{R_{LN} + G\} + \frac{m\gamma}{\Delta + (1 + r_{sdn}/r_a)\gamma} E_{ap}$$

where R_N = daytime net radiation

R_{LN} = night-time net long-wave radiation

G = soil heat flux

E_{ap} = Penman's aerodynamic term

4. Calculations of potential transpiration, potential evaporation and potential soil moisture deficit using the combination equation.

Using the 7-year monthly averages of meteorological variables for Kew employed by Wales-Smith and Bader (1979), their approximate values of B and G and reasonable monthly average values of r_{sdn}/r_a as implied by Thom and Oliver (1977), step-by-step calculation of E_t is given in Tables 3 and 4 of Evap. Mem. 47a. The results, for Kew, are reproduced here in Table 1. In these calculations m is taken as 1.5, appropriate to grassland at Kew. Values of Penman's E_{tp} (obtained from the same data by Wales-Smith and Bader (1979)) are given for comparison.

These results are shown in figure 1. It is noticeable that the ventilation (aerodynamic) component of E_{t400} is a considerably larger proportion of the whole than is that of E_{tp}. E_{t400} and E_{tp} are approximately equal in March and September, E_{t400} being higher than E_{tp} in the winter and lower in the summer.

The effects of varying m and of introducing G and r_L and correcting R_{LP} are shown, for 1964-70 at Kew, in Table 2.

Thom and Oliver (1977) proposed an equation following Penman (1948) and Monteith (1965) and including their own results on the ventilation (aerodynamic) term to estimate actual evapotranspiration. The results of calculations using their equation, the 1964-70 average data for Kew and their values of r_s/r_a (where r_s is approximate actual bull stomatal resistance) are given in Table 3. Also shown are the corresponding values of E_{t400}. It should be remembered that m is taken as 2.5 in both sets of calculations, hence the comparison is between comparable estimates of actual evapotranspiration and potential transpiration.

A convenient way of calculating E_p, the evaporation of intercepted rainfall, etc, is to multiply an E_t estimate by the fraction

$$\frac{\Delta + (1 + r_{sdn}/r_a)\gamma}{\Delta + \gamma}$$

this has the same effect as setting r_{sdn} to zero and solving the combination equation for E_p instead of for E_t.

Monthly values of the fraction are obtained in Table 4 for $z/z_o = 400$ ie vegetation height = .05m = 5cm and hence Z_o = 0.5cm. The inverse of this factor is the "amount of E_t required to evaporate 1mm of intercepted water".

Using the averages of measured day-time and night-time net radiation employed by Wales-Smith and Bader (1979), values of the day-time and night-time energy balance term were calculated. It was assumed that the day-time and night-time total values of the aerodynamic term are roughly equal from November to February and that the term is three times as large by day than by night over the remainder of the year (ie that K = 0.5 Nov-Feb and 0.75 Mar-Oct). It was also assumed that the contribution of net soil heat flux to potential evaporation must be $\geq$ 0 by night. From these data and assumed data, average values of E_t(day), E_p(day) and E_p(night) were calculated.

The minimum value of 24-hour potential evapotranspiration occurs when

surfaces are dry by day and night and $E_{24(min)} = E_{t(day)}$. The maximum occurs when surfaces are wet throughout and $E_{24(max)} = E_{p(day)} + E_{p(night)}$.

Using the results obtained in Table 4 calculations are made in Table 5 in order to take into account the evaporation of intercepted rainfall on the basis of the average numbers of days each month having given falls.

The 24-hour values of intercepted rainfall, r_i, for March and October agree with the 1mm per rain day assumed by Thom and Oliver (1977) and those for the winter months are reasonably taken as $<$ 1mm on the grounds of low actual evaporation on wet, winter days, relatively shorter grass than in other seasons. Values of up to 2.5mm per rain day are allowed, in summer, because of the showery nature of much summer rainfall.

The fractions of total rain falling by day and night are assumed to be related to day-length from October to March and to take arbitrarily chosen values in other months. The number of days with $\geq$ 1mm of rain per month is assumed to be $\approx$ 10 based on an analysis of data from St James's Park for the period 1961-1975. The r_i estimates on line 5 are multiplied by 10 to give monthly estimated totals of r_i (line 9). The day-time and night-time totals of r_i are set out in lines 10 and 11, obtained by applying the factors in lines 6 and 7 to the values in line 9. The totals of day-time evaporation of intercepted water are assumed equal to "r_i day-time total" (line 10). The latter values are multiplied by the "amounts of E_t to evaporate 1mm of water" (Table 4) and the results subtracted from E_t(day) (Table 4) to give day-time residual E_t (line 13). Estimates of maximum possible night-time E_w are obtained by taking the smaller of daily night-time E_p (line 3) multiplied by 10 and night-time r_i (line 11). The sum of the three quantities E_w(day) (day-time evaporation of intercepted rainfall and dew), $E_t(\text{residual})_{day}$ (day-time transpiration from dry vegetation) and E_w night (night-time evaporation of intercepted rainfall) gives rough estimates of monthly average totals of potential transpiration and evaporation (evapotranspiration). The nocturnal evaporation of dew is assumed to be taken care of in positive values of night-time E_p.

The totals of potential transpiration and evaporation (E) are compared with monthly average rainfall totals (1964-70) from Kew in lines 16 and 17. Rough values of month-end potential soil moisture deficit are given in line 18.

The values of E/E_{tp} given in line 19 should be comparable with the values of E_{LYS}/E_{tp} obtained by Wales-Smith (1975) since E is an estimate of potential evapotranspiration. The two sets of monthly ratios are compared in Figure 2 (the ratio E_{TANK}/E_{tp} is also shown). The agreement is very good.

In Figure 3 a comparison is made of values of E_{400} ($E_{24(max)}$, E and $E_{24(min)}$) based on E_{t400} (for short grass) and Penman's E_{tp}. The last named is below the E_{400} value for a completely dry month from September to January and equals the value for permanently wet surfaces from May to July.

5. The operational use of estimates of potential transpiration and evaporation in calculating changes in soil moisture deficit and amounts of hydrologically effective rainfall

1. Ideally E_t and E_p would be calculated on an hourly time-step and balanced against hourly rainfall totals. Appropriate E_p rates would be calculated and used during rainfall and as long thereafter as the surface of vegetation were assumed to be wet. Night-time, positive E_p values would be ignored when surfaces were dry. Night-time, negative E_p values would be treated as condensation to be evaporated by subsequent E_p obtained from E_t the following day.

2. In practice the most relistic option currently available is probably to calculate E_t and E_p separately or to divide 24-hour E_t, arbitrarily between day and night. If rainfall totals are not available for day and night, separately, an arbitrary division could be made.

3. The following maximum amounts of intercepted rainfall for grasslands are proposed:-

	J	F	M	A	M	J	J	A	S	O	N	
mm per rain day	.2	.3	.5	1.2	1.9	2.1	2.1	1.9	1.2	.5	.3	.2
mm per rain night	.3	.5	.5	.6	.6	.4	.4	.6	.6	.5	.5	.3

4. Any intercepted rainfall not evaporated by day (ie on a dull, wet day) or night would be carried forward until evaporated. Under these circumstances night-time values of r_l could be as large as but not larger than day-time values.

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Table 1. Values of average E_{t400}, E_{tP} and their ventilation components at Kew 1964-70

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
E_{t400}	9·9	15·8	33·6	48·0	70·6	87·8	88·4	73·7	48·0	26·5	14·1	9·3	
$\frac{1.5\gamma}{\Delta+(1+r_{sen}/r_a)\gamma} E_{ap}$	16·3	14·5	25·1	27·0	31·1	37·1	37·8	32·0	23·8	17·7	13·9	10·9	
E_{tP}	5·4	14·2	33·5	52·3	79·6	96·3	94·7	76·2	45·7	20·6	7·5	3·4	
$\frac{\gamma}{\Delta+\gamma} E_{ap}$	10·3	13·8	20·9	21·6	24·2	28·0	28·2	23·9	17·6	13·9	12·4	9·9	

Table 2. Values of percentage change in average monthly E_{t100} at Kew (1964-70) result from changing m, introducing G and $(1-r_L)B$

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Decrease m from 2·5 to 1·9	-18	-13	-12	-12	-9	-10	-10	-10	-10	-15	-16	-18	
Decrease m from 2·5 to 1·5	-33	-25	-22	-20	-15	-16	-16	-16	-18	-24	-29	-33	
Introduce G	+12	+4	-1	-5	-6	-5	-5	-2	+3	+12	+19	+20	
Correct R_{LP} and introduce r_L	+1	-1	-1	-2	-3	-3	-3	-3	-4	-3	-2	0	

Table 3 Comparison of Thom and Oliver E_{A100} and E_{t100} for Kew 1964-70

E_{A100}	12·1	20·2	38·1	51·6	74·2	91·7	92·4	75·2	47·4	26·2	15·4	10·4	
E_{t100}	14·7	21·1	43·3	59·7	83·2	104·2	105·6	88·1	58·7	35·0	19·8	13·8	

Table 4 Values of $E_{t(day)}$, $E_{p(day)}$ and $E_{p(night)}$ for Kew 1964-70 for E_{t400}

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
$\Delta+(1+r_{san}/r_a)\gamma$	1·73	1·80	1·75	1·72	1·91	2·07	2·14	2·11	1·97	1·88	1·82	1·72	
$\Delta+\gamma$	1·265	1·262	1·323	1·430	1·632	1·822	1·910	1·879	1·753	1·589	1·361	1·266	
$\frac{\{\Delta+(1+r_{san}/r_a)\gamma\}}{\Delta+\gamma}$	1·37	1·43	1·32	1·20	1·17	1·14	1·12	1·12	1·12	1·18	1·34	1·36	
E_t to evap. 1 mm r_i	·73	·70	·76	·83	·85	·88	·89	·89	·89	·85	·75	·74	
$\{\Delta/\Delta+(1+r_{san}/r_a)\gamma\}R_{N\,day}$	1·6	4·3	14·8	28·0	47·9	59·7	60·2	49·3	31·5	13·2	2·7	1·0	
$K\{1.58\Delta/\Delta+(1+r_{san}/r_a)\gamma\}E_{ap}$	5·7	7·3	15·9	20·3	23·3	27·8	28·3	24·1	17·6	11·8	6·9	5·5	
$N\{\Delta/\Delta+(1+r_{san}/r_a)\gamma\}G$	+0·9	+0·5							+1·3	+2·2	+1·6	+1·1	
$\{\Delta/\Delta+(1+r_{san}/r_a)\gamma\}G$			-0·6	-3·5	-5·7	-6·7	-5·8	-1·9					
$E_{t(day)}$	8·2	12·1	30·1	44·8	65·5	80·8	82·7	71·5	50·4	27·2	11·2	7·6	
$E_{p(day)}$	11·2	17·3	39·7	53·8	76·6	92·1	92·6	80·1	56·5	32·1	15·9	10·3	
$\{\Delta/\Delta+\gamma\}R_{N(night)}$	-7·3	-7·9	-6·9	-5·0	-4·6	-4·0	-4·6	-5·3	-6·2	-8·0	-9·4	-6·3	
$(1-K)\{1.58\Delta/\Delta+\gamma\}E_{ap}$	8·0	10·2	9·2	6·2	6·6	7·4	7·5	6·3	4·8	5·4	8·5	7·3	
$(1-N)\{\Delta/\Delta+\gamma\}G$	+1·8	+0·9							+0·3	+2·1	+3·2	+2·7	
$E_{p(night)}$	2·5	3·7	2·3	1·2	2·0	3·4	2·9	1·0	-0·6	-0·5	2·3	3·7	
$E_{24(min)} = E_{t(day)}$	8·2	12·1	30·1	44·8	65·5	80·8	82·7	71·5	50·4	27·2	11·2	7·6	
$E_{24(max)} = E_{p(day)} + E_{p(night)}$	13·7	21·0	42·0	55·0	78·6	95·5	95·5	81·1	56·5	32·1	17·3	14·0	

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Table 5 Values of stage calculations in approximating potential evapotranspiration E_{1400}

at Kew (1964-70) based on E_{t1400}.

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
1. Day-time E_t	0·3	0·4	1·0	1·5	2·1	2·7	2·7	2·3	1·7	0·9	0·4	0·3	
2 Day-time E_p	0·4	0·6	1·3	1·8	2·5	3·1	3·0	2·6	1·9	1·0	0·5	0·3	
3 Night-time Ep	0·1	0·1	0·1	0	0·1	0·1	0·1	0	0	0	0·1	0·1	
4 24-hr Ep (E_{p24})	0·5	0·7	1·4	1·8	2·6	3·2	3·1	2·6	1·5	1·0	0·6	0·4	
5 Estimated 24-hr r_i (may not exceed E_{p24}	0·5	0·7	1·0	1·8	2·5	2·5	2·5	2·5	1·8	1·0	0·6	0·4	
6 Fraction of r by day	·33[2]	·42[2]	·49[2]	·67[1]	·75[1]	·85[1]	·85[1]	·75[1]	·67[1]	·54[2]	·37[2]	·33[2]	
7 Fraction of r by night	·67[2]	·58[2]	·51[2]	·33[1]	·25[1]	·15[1]	·15[1]	·25[1]	·33[1]	·46[2]	·63[2]	·67[2]	
8 No of (24 hr) days when $r \geq 1{\cdot}0$ mm	10	10	10	10	10	10	10	10	10	10	10	10	
9 Monthly total r_i	5	7	10	18	25	25	25	25	18	10	6	4	
10 Day-time total r_i mm	1·7	2·9	4·9	12·1	18·7	21·3	21·3	18·7	12·1	4·6	2·2	1·3	
11 Night-time total r_i mm	3·3	4·1	5·1	5·9	6·3	3·7	3·7	6·3	5·9	5·4	3·8	2·7	
12 Day time actual E_w	1·7	2·9	4·9	12·1	18·7	21·3	21·3	18·7	12·1	4·6	2·2	1·3	
13 Day time $E_{t(resid)}$	7·0	10·1	26·4	34·8	49·6	62·1	63·7	54·9	39·6	23·3	9·5	6·6	
14 Night-time max E_w	2·5	3·7	2·3	1·2	2·0	3·4	2·9	1·0	0	0	2·3	2·7	
15 $E = E_{w(day)} + E_{w(night)} + E_{t(resid)}$.	11·2	16·7	33·6	48·1	70·3	86·8	87·9	74·6	51·7	27·9	14·0	10·6	
16 Approx E	11	17	34	48	70	87	88	75	52	28	14	11	
17 Approx $\bar{r}$	44	35	43	56	52	52	63	64	55	45	64	58	
18 Approx PSMD					18	53	78	89	86	69	19		
19 E/E_t ratio	2·07	1·18	1·00	0·92	0·88	0·90	0·93	0·98	1·13	1·35	1·87	3·12	

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1 arbitrary percentages assumed

2 approximate day and night fractions.

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Table 5 (cont'd) Values of stage calculations in approximating E_{100} from E_{t100}

at Kew 1964–70

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
E_{t100}	14·7	21·1	43·3	59·7	83·2	104·2	105·6	88·1	58·7	25·0	19·8	13·8	
E_{t100} (day)	10·1	15·0	37·2	54·9	77·4	94·8	97·1	82·8	56·9	32·5	14·3	8·8	
"E_{t100} (night)"	4·6	6·1	6·1	4·8	5·8	9·4	8·5	5·3	1·8	2·5	5·5	5·0	
r_i day	1·7	2·9	4·9	12·1	18·7	21·3	21·3	18·7	12·1	4·6	2·2	1·3	
r_i night	3·3	4·1	5·1	5·9	6·3	3·7	3·7	6·3	5·9	5·4	3·8	2·7	
E_w (day)	1·7	2·9	4·9	12·1	18·7	21·3	21·3	18·7	12·1	4·6	2·2	1·3	
E_t (resid)	9·0	13·3	34·0	45·7	62·8	77·3	79·5	67·3	47·1	28·9	12·9	8·0	
E_w (night)	3·3	4·1	5·1	5·9	6·3	3·7	3·7	6·3	2·2	3·2	3·8	2·7	
E_{100}	14·0	20·3	44·0	63·7	87·8	101·3	104·5	92·3	61·4	36·7	18·9	12·0	
E_{100}/E_{te}	2·59	1·43	1·31	1·22	1·10	1·06	1·10	1·21	1·34	1·78	2·52	3·53	

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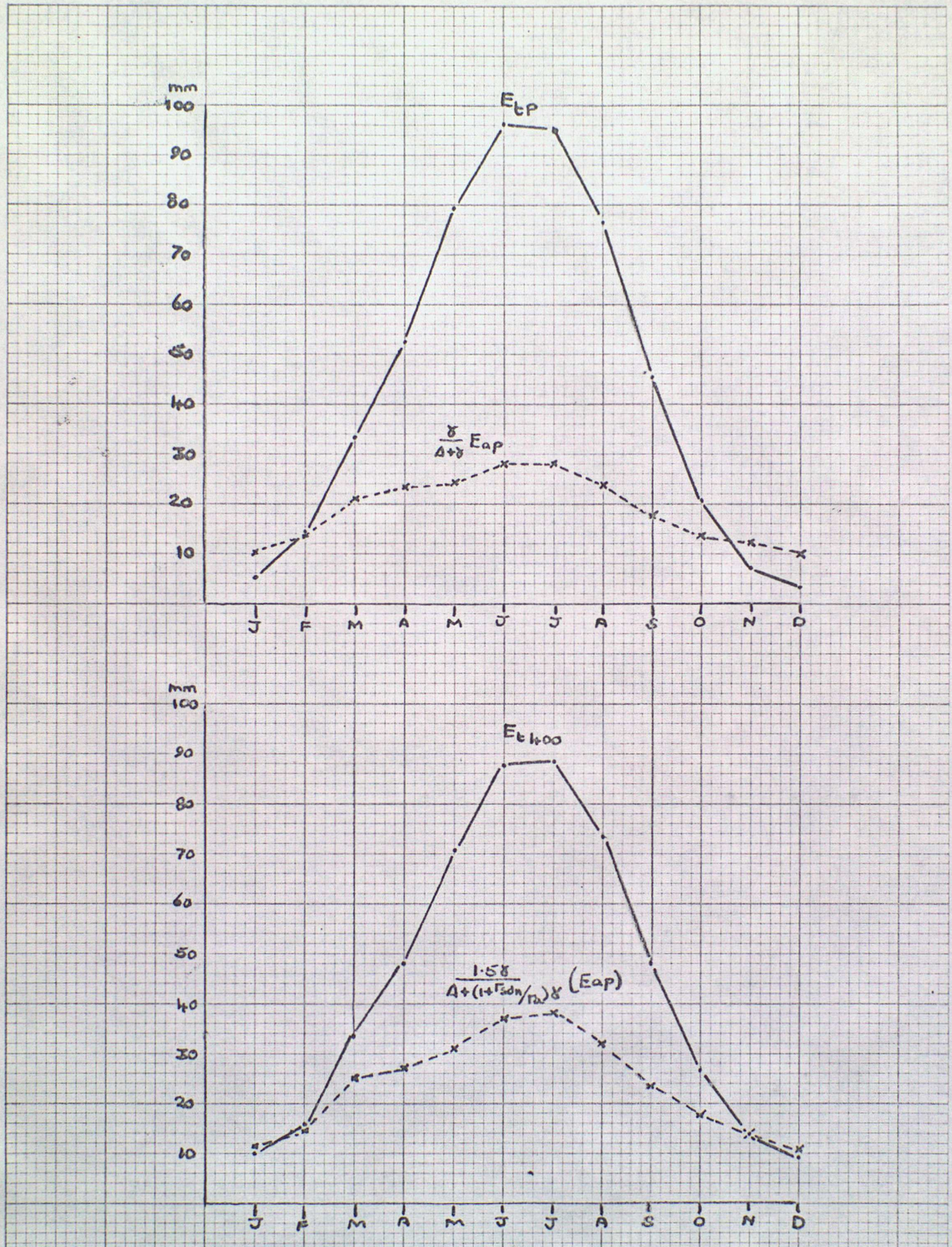

Figure 1. Estimates of 1964-70 average potential transpiration from grass at Kew.

Figure 2. Comparisons of three sets of monthly average relationships between measures of potential evaporation.

Δ — Δ $\left\{E_{w(day)} + E_{t(resid)} + E_{w(night)}\right\} / E_{tP}$ (Kew 1964-70)

x - - - x E_{LYS}/E_{tP} (53 station-years)

• — · — · E_{TNK}/E_{tP} (34 station-years)

Figure 3

Kew
1964-70
*(based on E_{t400}) for grass.

•——• E = potential evapotranspiration (line 16, Table 5)*

x---x E_{TP} = Penman's E_t (Table 1)

x·····x $E_{24(max)}$ = Max. possible E (assuming wet surfaces throughout)*

⊙·····⊙ $E_{24(min)}$ = Min. possible E (assuming no rain!)*